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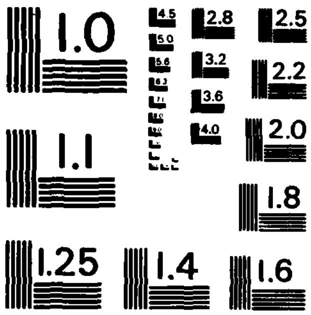

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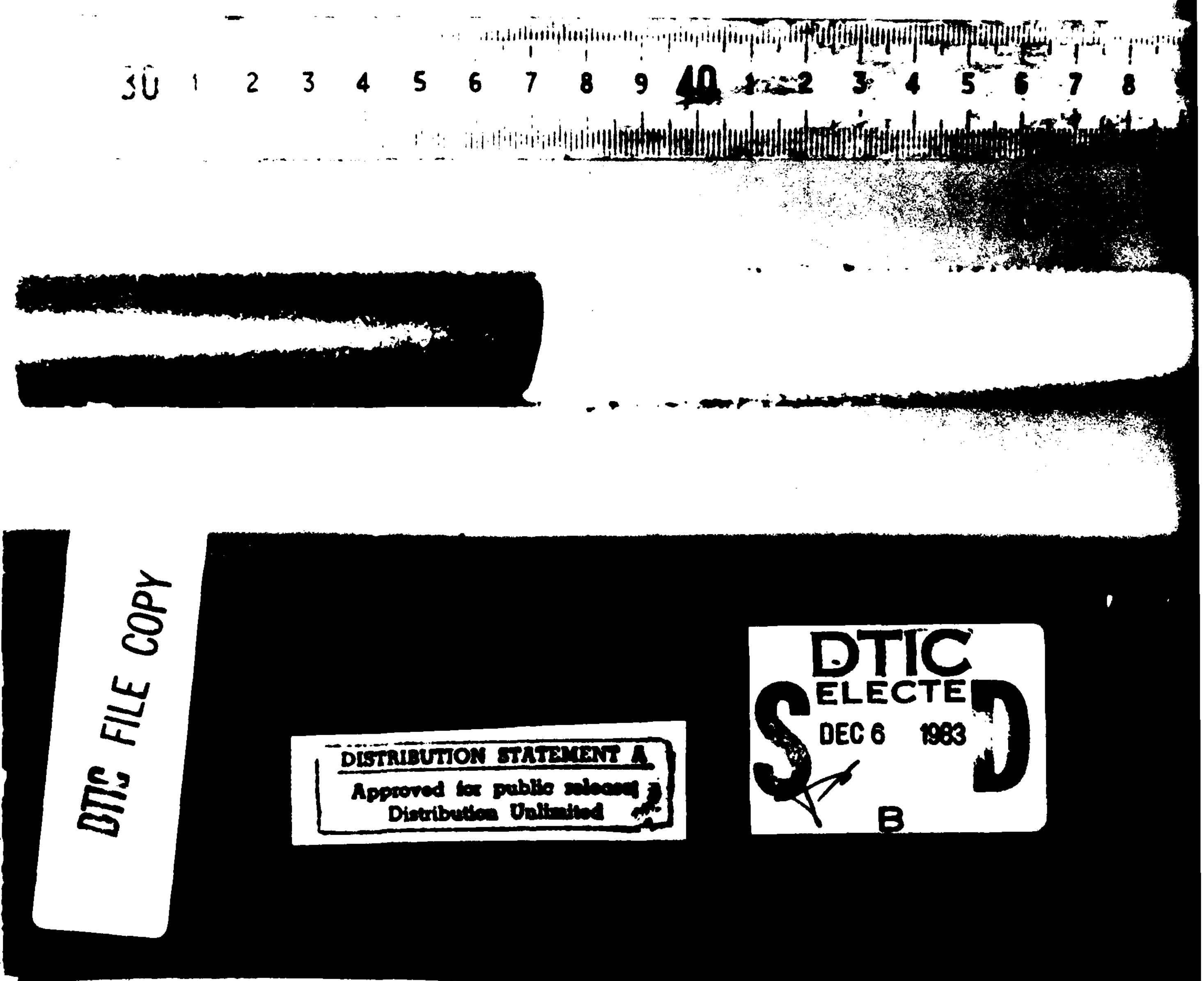
US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

Mechanical ice release processes

I. Self-shedding from high-speed rotors



For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Ice accreted on a high-speed rotor.
(Scale is in centimeters.)

CRREL Report 83-26

October 1983

Mechanical ice release processes

I. Self-shedding from high-speed rotors

K. Itagaki

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Ice accreted on high-speed rotors operating in supercooled fog can be thrown off by centrifugal force, creating severe unbalance and dangerous projectiles. A simple force balance analysis indicates that the strength of accreted ice and its adhesive strength can be obtained by measuring the thickness of the accretion, the location of the separation, the rotor speed, and the density. Such an analysis was applied to field and laboratory observations of self-shedding events. The results agree reasonably well with other observations.

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PREFACE

This report was prepared by Dr. Kazuhiko Itagaki, Research Physicist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for this research was provided by DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground,* Task C, *Research in Terrain and Climatic Constraints,* Work Unit 002, *Adhesion and Physics of Ice.*

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MECHANICAL ICE RELEASE PROCESSES
I. Self-shedding from High-speed Rotors

K. Itagaki

INTRODUCTION

Ice adhesion and its control have been studied through various approaches. Although many experimental studies stressed careful preparation of the substrate surfaces and ice, the results always had considerable scatter. Efforts were concentrated on making the results reproducible by refining the alignment and procedure of surface preparation. Since most of the studies used a chemical approach, little consideration was given to the fracture aspects of the ice, the strength of the ice/substrate interface, or the deviation from pure shear or tensile conditions. Pure tensile tests, for instance, cannot be carried out within the limit of finite dimensions because the difference between the elastic moduli of the ice and the substrate creates a peeling effect at the edge of the ice-substrate bond. The weakest point in the bond system dictates the strength of the entire system.

Most of the theoretical studies concentrated on control of the surface energy. Initiation and propagation of a crack leading to the final catastrophic fracture were of little concern. A vague notion that stronger bonding will result in higher adhesive strength seems to prevail. However, as I discussed in a recent report (Itagaki 1983) the surface energy only indirectly controls the adhesive strength of ice through surface contamination. On the very clean surface, ice tends to break before the bond fails.

In this paper, I will use theoretical and experimental analyses to examine one "real-world" process of mechanical ice removal, the self-shedding of ice from rotating struts.

Under icing conditions, high-speed rotors, such as aircraft propellers, main and tail rotors of helicopters, and turbines of wind energy generators, can be dangerous to operate. One of the major causes of danger is the self-shedding of ice built up on the rotor. When ice is shed from one blade of a rotor, a helicopter may become uncontrollably unbalanced, and dangerous high-speed projectiles may damage airframes or nearby structures. Many factors are involved in the self-shedding process: the balance of forces, the initiation and propagation of a local fracture, and the eventual release of accreted ice. This analysis is limited to the examination of the balance of forces. Such simple analysis, however, leads us to a new method of measuring adhesive and tensile strength of accreted ice simultaneously.

THEORETICAL ANALYSIS

The balance of force for a simple case is shown in Figure 1. A rectangular bar of components A and B is bonded at an interface having cross-sectional area S_c perpendicular to the radial direction. As this bar is rotated around an axis located at the end of component A, the centrifugal force F_t acting on S_c is

$$F_t = \int_{l=r}^{R} l\omega^2 \rho\, S_c\, dl \qquad (1)$$

where r = distance from the axis to the interface
ω = angular velocity
R = radius of the rotor.

Component B will break away if $F_t > A_t \cdot S_c$, where A_t is the tensile adhesive strength between substrates A and B. If component B is accreted ice having

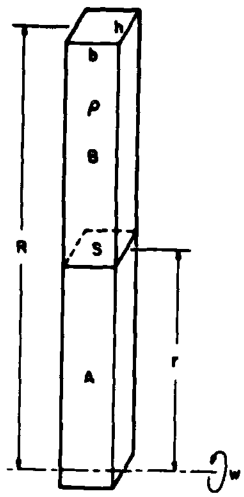


Figure 1. Schematic diagram of a composite rotor having joint at S.

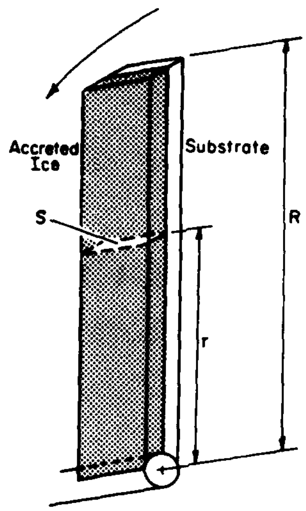


Figure 2. Ice accreted on the rotor substrate.

uniform thickness h, width b and density ρ, eq 1 can be simplified to

$$F_t = \frac{\omega^2 \rho b h}{2} (R^2 - r^2) > A_t \cdot S_c = A_t b h. \quad (2)$$

When ice accretes on a rotor, the geometry is as shown in Figure 2. The ice accreted on the substrate on the outboard side of imaginary cross section S is supported by a combination of the shear adhesive force F_a and the tensile force F_t. The accreted ice will separate at S when the centrifugal force on the outboard side of S exceeds the supporting force available from the combination of the adhesive strength $A_s \cdot S_a$ and tensile strength $T \cdot S_c$, where A_s is the shear adhesive strength between the accreted ice and the substrate, S_a is the area of contact between the ice and the rotor outboard of the cross section S, and T and S_c are the tensile strength and the cross-sectional area of the accreted ice, respectively. The difference between the supporting forces and the centrifugal force F_c is a supporting force margin M:

$$M = (T \cdot S_c + A_s \cdot S_a) - F_c \, . \quad (4)$$

Shedding will occur when M becomes negative.

If the accreted ice has uniform width b and thickness h, then

$$M = Tbh + A_s (R - r) b - (R^2 - r^2) \, \omega^2 \rho b h / 2 \quad (5)$$

where Tbh is the tensile supporting force and $A_s(R - r)b$ is the shear adhesive supporting force. The relationship between M and r for different thicknesses is shown in Figure 3. The curves are a set of parabolas having nodes at $r = \pm \sqrt{R^2 - 2T/\omega^2 \rho}$, $M = A_s (R - r)$. As the thickness h increases, the part of the curves between the nodes lowers, and M decreases and eventually becomes negative. The self-shedding most likely begins when the supporting force margin becomes zero. If $M = 0$, then eq 5 becomes

$$r = \frac{A_s \pm \sqrt{A_s^2 - 2h\omega^2 \rho \, [A_s R - h(R^2 \omega^2 \rho / 2 - T)]}}{h \omega^2 \rho} \, . \quad (6)$$

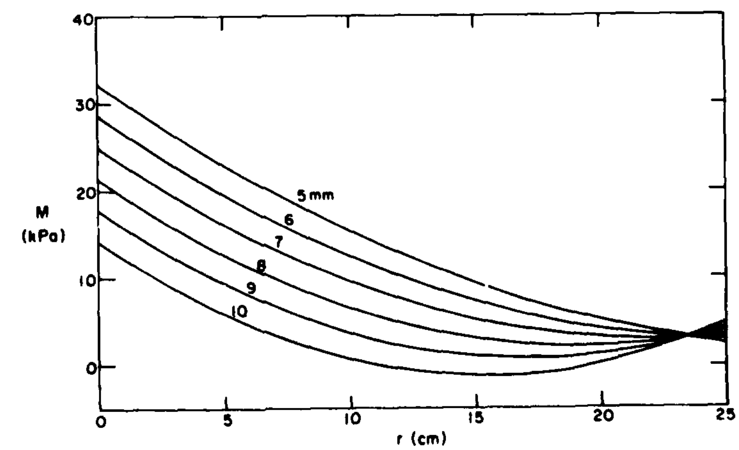


Figure 3. Radial variation of supporting force margin with thickness.

The solution becomes real when the curve is tangential to the abscissa, that is, when the two roots meet; therefore, the square root term in eq 6 becomes zero:

$$A_s^2 - 2h\omega^2 \rho A_s R + 2h^2 \omega^2 \rho (R^2 \omega^2 \rho/2 - T) = 0. \tag{7}$$

From eq 7 the ice thickness h is

$$h = \left[\frac{\omega\rho R \pm \sqrt{2\rho T}}{2\omega\rho(R^2\omega^2\rho/2 - T)}\right] A_s . \tag{8}$$

The accreted ice will most likely start to shed at this thickness. Since the square root term in eq 6 vanishes at this thickness, eq 6 can be simplified by using eq 8:

$$r = A_s/h\omega^2\rho = \frac{R^2\omega^2\rho - 2T}{(\omega\rho R \pm \sqrt{2\rho T})\omega}$$

$$= \frac{R\omega\rho \pm \sqrt{2\rho T}}{\omega\rho} . \tag{9}$$

The negative sign of the square root should be used to keep $r < R$. Note that no adhesive force term is involved in this equation.

Solving this equation for T, we obtain the tensile strength of accreted ice by knowing the density of accreted ice ρ, the angular velocity ω, the radius of the rotor R, and the location of the failure surface r:

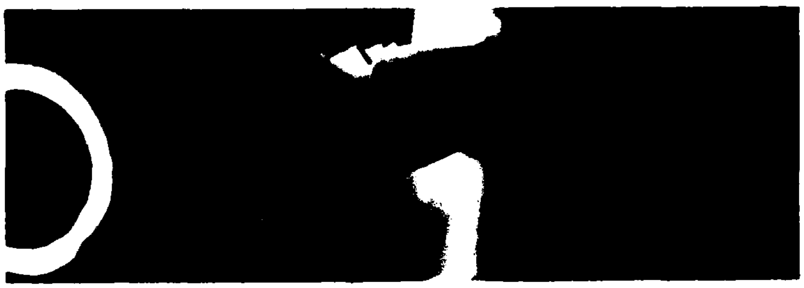
$$T = \frac{\omega^2\rho (R - r)^2}{2} . \tag{10}$$

Since we can measure the thickness where the failure started, we can calculate the adhesive strength of the accreted ice from eq 9:

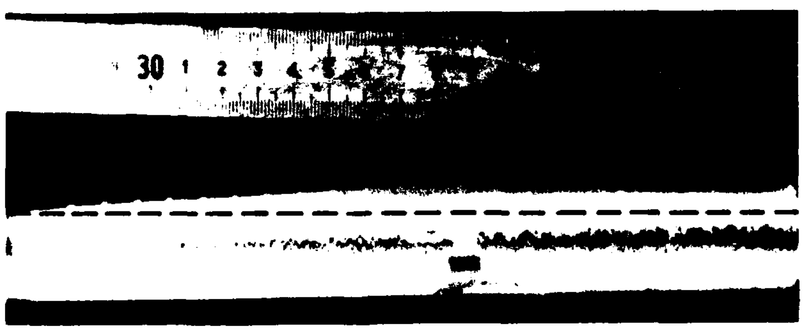
$$A_s = \frac{h\omega\rho (R^2\omega^2\rho - 2T)}{\omega\rho R + \sqrt{2\rho T}} . \tag{11}$$

CALCULATED TENSILE AND ADHESIVE SHEAR STRENGTH FROM EXISTING EXPERIMENTAL RESULTS

The analysis described here is based on the assumption that the accreted ice has a uniform cross-sectional area along the rotor. This assumption is justified under certain conditions. Near the transition from dry- to wet-growth regime the thickness of the accreted ice across the failed surface and the thickness of the ice on the other side of the rotor blade are reasonably uniform (Fig. 4). Smooth, crescent-



a. Perpendicular to the radial direction.



b. Parallel to the radial direction.

Figure 4. Thickness of accreted ice (shown between dashed lines). The thickness is uniform slightly below the wet- and dry-growth regime boundary.

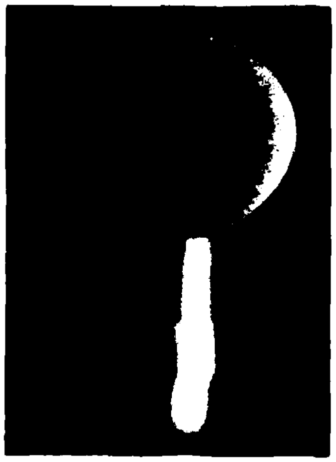


Figure 5. Crescent-shaped cross section of accreted ice grown under dry-growth conditions.

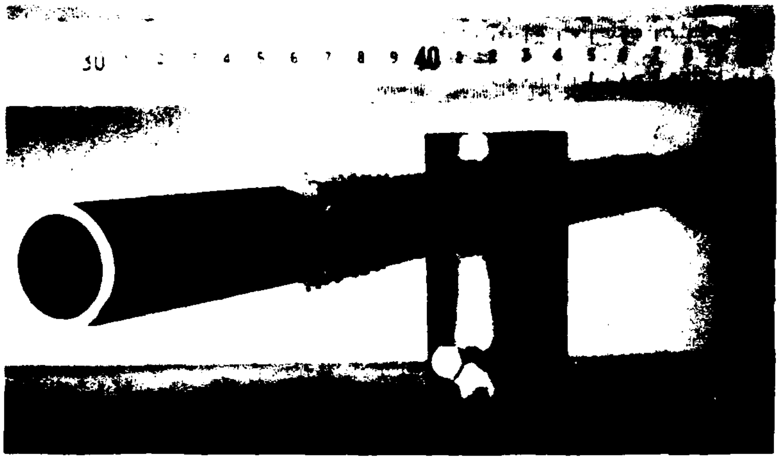


Figure 6. Rough, icicle-covered accretion grown in the wet-growth regime.

shaped growth is usually observed in the pure, dry-growth regime (Fig. 5). Rough, icicle-covered surfaces are formed in the wet-growth regime (when the temperatures are at or near the freezing point) (Fig. 6). Numerical integration using eq 1 would be needed to obtain accurate tensile and adhesive strength values when the surface conditions are not uniform.

During laboratory icing experiments on the high-speed radar (Ackley et al. 1979) several self-shedding events were observed. The observed data and the tensile and adhesive strengths calculated from the data using eq 10 and 11 disregarding the thickness variation are summarized in Table 1. Self-shedding observed during field tests made at the summit of Mt. Washington (Itagaki et al. 1983) is also included.

Experiments 1, 2, 3, 10 and 11 had cross sections similar to those shown in Figure 4, so eqs 10 and 11 can be used. However, except for experiment 7 the data agree reasonably well within the variation expected from experimental error. In experiment 7

Table 1. Calculated tensile and adhesive strength of accreted ice.

Exp. no.	Exp. code	Date	Temp. (°C)	Elapsed time (s)	Density (g/cm^3)	Shedding radius (cm)	Thickness (cm)	Growth rate (mm/s)	Rotor speed (rpm)	T (kPa)	A_s (kPa)	Shape of accretion
					Laboratory experiments, R = 25 cm (Ackley et al. 1979)							
1	T-12-11	8/26/77	-11.1	105	0.91	15.55	0.346	0.0329	3600	77.5	69.9	Uniform
2	T-14-77	9/7/77	-13.3	123	0.90	16.5	0.374	0.0304	3600	462.1	78.1	Uniform but curved fracture surface
3	T-16-77	9/9/77	-15.5	150	0.90	15.5	0.596	0.0397	3600	577.2	118.2	Uniform
4	T-4-77-2	10/28/77	-1.0	123	0.92	10.8	0.21	0.0171	3600	1318.2	29.7	Irregular
5	T-6-77-2	11/7/77	-5.0	114	0.92	15.4	0.399	0.035	3600	602.5	80.3	Irregular
6	T-8-77-1	11/8/77	-5.0	161	0.92	17.1	0.52	0.0323	3600	408.0	116.3	Irregular
7	TR-8250	9/10/78	-4.0	300	0.92	24.6	0.34	0.0113	1800	0.26	27.3	Irregular; only tip shed
8	TR-9303	10/30/79	-14.5	365	0.9	6.5	0.5	0.0137	3600	2188.8	41.6	Crescent
					Natural icing at Mt. Washington, R = 75 cm (Itagaki et al. 1983)							
9	14 Jan 801 IB	1/14/80	-5.0	470	0.9	49.2	1.0	0.0212	1800	1064	157.3	Uniform on the airfoil blade
10	14 Jan 801 PC	1/14/80	-5.0	470	0.9	42.5	0.42	0.0089	1800	1680	57.1	Uniform on greased cylinder
11	14 Jan 802 PC	1/14/80	-3.0	350	0.9	50.3	0.38	0.0108	1800	975	61.1	Uniform

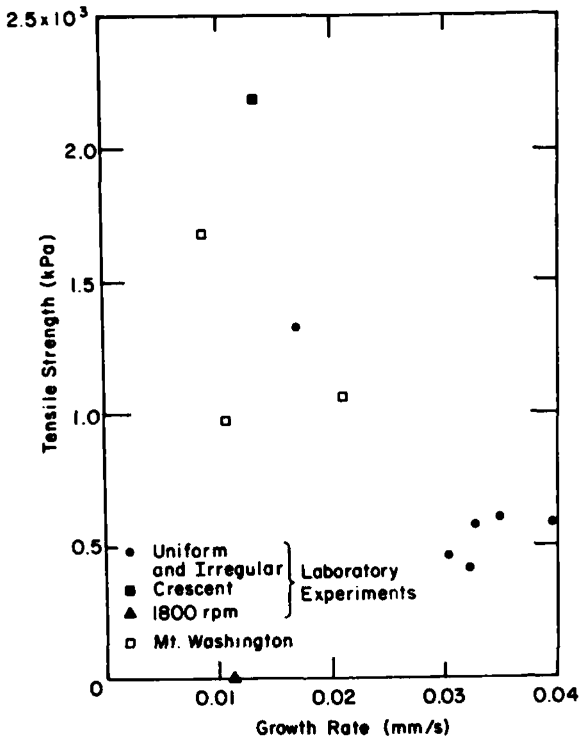


Figure 7. Growth rate vs tensile strength of accreted ice. Slower-grown ice is stronger.

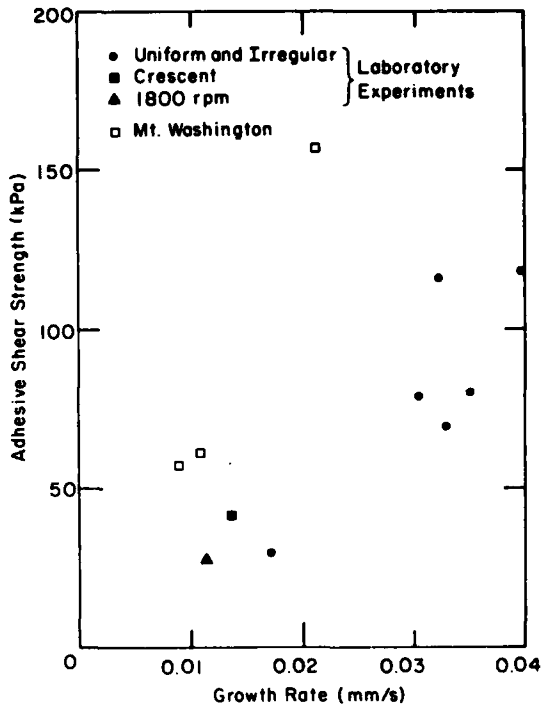


Figure 8. Growth rate vs adhesive shear strength. Faster-grown ice has a higher shear adhesive strength.

the ice shed at the very tip of the rotor, so the results are questionable.

The tensile strengths of accreted ice at slow growth rates were about 1-2 MPa, while those of more rapidly grown ice were 0.5-0.6 MPa (Fig. 7). However, adhesive shear strength was greater at faster growth rates (Fig. 8). If we place the Mt. Washington tests in a separate group, the tendency becomes more pronounced in both groups. Tensile and adhesive shear strengths show little dependence on temperature (Figs. 9 and 10). The shear adhesive strength values calculated from the thickness, the location of separa-

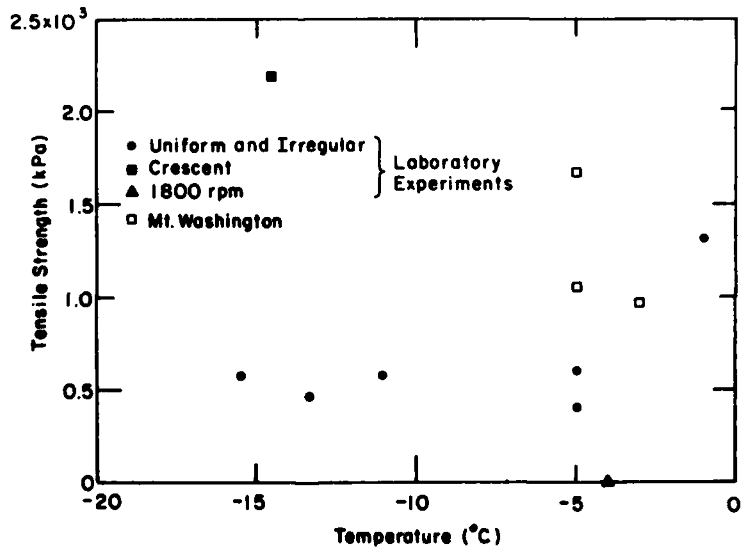


Figure 9. Temperature vs tensile strength. This shows little relationship.

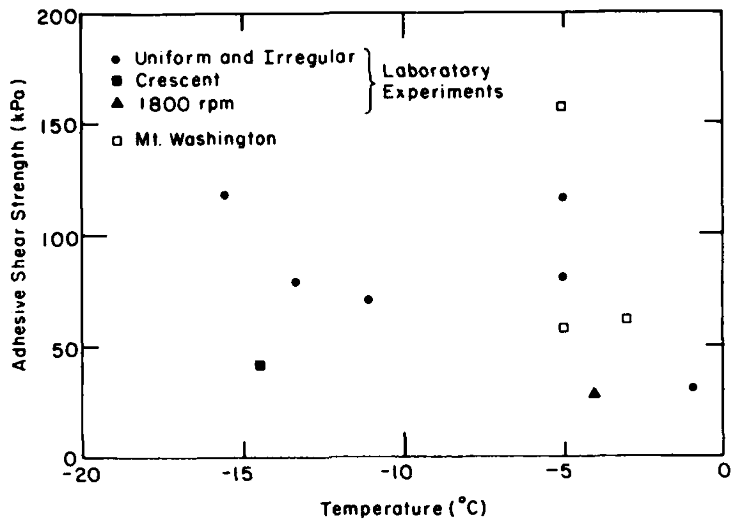


Figure 10. Temperature vs shear adhesive strength. This also shows little relationship.

tion and the density were within the range of 30–150 kPa, which roughly agrees with the values obtained by various researchers on slightly contaminated, smooth-mirror-finished metal surfaces.

COMPARISON WITH PREVIOUS EXPERIMENTAL STUDIES

Beams et al. (1955) were probably the first to use the centrifugal force field on the high-speed rotor as a tool for studying adhesive and tensile strength. When a uniform, continuous film is deposited on an ultra-high-speed rotor, a combination of hoop tensile stress and tensile adhesive strength supports the adhered film on the rotor against the centrifugal force, while only tensile adhesive strength supports the discontinuous film removed from the rotor. They did not apply this method to ice adhesion problems.

Many researchers have reported on adhesion of pure and doped ice on various substances with a variety of surface treatments and coatings. The results ranged from an extremely low 50 mPa, attributable to viscous sliding on a smooth, oil-coated surface (Baker et al. 1962), to high values of 2734 kPa (Jones and Gardos 1972), which should be regarded as a confined shear test of ice itself. Raraty and Tabor (1958) gave another very high value of 1960 kPa at -10°C on stainless steel polished by #600 Carborundum and cleaned with an HNO_3-alcohol mixture. Bascom et al. (1969) obtained slightly lower values of 930 kPa by using stainless steel polished with 0.05-μm alumina. Ford and Nichols (1961, 1962) give even lower values of 750 kPa on stainless steel polished by alumina of unknown grade.

Jellinek (1957a, b, 1960) studied the effects of sample size, surface roughness and temperature extensively. However, the substrates were immersed in benzene before testing, which presumably lowers the adhesive strength (Raraty and Tabor 1958). His results were generally lower than those of the other researchers.

Yano and Kuroiwa (1979) were apparently the first to measure the adhesive tensile strength of ice on a metal substrate by using the centrifugal force field from a rotor with a speed much lower than that used by Beams et al. (1955). Their system has a well-defined geometry similar to Figure 1, but it cannot measure tensile strength. They measured tensile adhesive strength of pure and KCl-doped polycrystalline ice on a polished but not mirror-finished brass surface. Their results at ambient temperatures higher than -10°C scattered between 50 and 900 kPa. As the temperature dropped, the adhesive strength rapidly increased to 2000–3000 kPa. Within this temperature range the breaks were mostly cohesive. Since the conditions of their testing are different from my studies, direct comparisons of the results are difficult.

Compared with the melt-grown ice usually used for studies like those described above, accreted ice may have different tensile and shear adhesive strengths, since it has a strongly oriented structure. The following studies were made by using accreted ice.

Kuroiwa (1951) studied ice accretions in natural

conditions at the top of Mt. Nisekoan-nupuri using a 270-cm-diameter metal propeller. The ice did not accrete beyond a certain radius of the propeller; this radius was proportional to the ambient temperature. If the radius of the ice accretion limit was the radius where self-shedding occurs, the tensile and adhesive strength of ice can be estimated from the photographs and drawings in this report. The results at -10°C of a tensile stength of 1960 kPa and an adhesive strength of 320 kPa are within the reasonable range. At -5°C the tensile strength calculated from his Figure 10 resulted in an unreasonably high value of 17,600 kPa; either the assumption of a uniform cross section and thickness cannot be applicable or some other mechanism, such as vibration of the blade or aerodynamic heating, may be causing the shedding.

One of Kuroiwa's observations is that the radius of the limit of ice accretion seldom exceeded 1 m, even though the ambient temperature dropped below -10°C. The temperature rise from aerodynamic heating due to friction at 1 m is 15.8°C, and that from adiabatic compression is 17.8°C, according to the theoretical calculations referred to in his paper [$\Delta\theta_1 = 3.43\times10^{-5}\ U^2$°C (km/hr)^2 for frictional heating and $\Delta\theta_2 = 3.87\times10^{-5}\ U^2$°C (km/hr)^2 for adiabatic compression (Pohlhausen 1921)]. Either of these heating mechanisms would be more than sufficient to bring the temperature above the freezing point.

The speed of the tip of the rotor used in the Mt. Washington measurements was 141 m/s, and the corresponding temperature rises from frictional and adiabatic heating were calculated to be 8.9° and 10.0°C, respectively, using the Pohlhausen equation. However, I observed ice accretion at ambient temperatures as high as -2°C. The temperature rise measured on the surface of the leading edge at the tip was 2-2.5°C, far lower than the calculated values. My measurements made on top of Mt. Washington indicated a rise of less than 3.0°C under the dry conditions at 0.75 m from the center. Under these conditions the heating can be regarded as purely aerodynamic. Extrapolated to 1 m, this temperature rise would be about 5.3°C. Apparently the calculations using the Pohlausen equation are too high. On the other hand the thickness at which self-shedding would occur at 1 m was calculated to be 5.4 mm by assuming that eqs 10 and 11 applied and that the tensile and shear adhesive strengths are the median values of 500 and 200 kPa, respectively. This thickness is quite reasonable, so Kuroiwa's observation may be caused by self-shedding.

Stallabrass and Price (1962) used centrifugal force on accreted ice to measure shear adhesive strength. Their conditions were closer to my analysis than most of the other studies. They tested five materials commonly used in aircraft structures: aluminum, stainless steel, titanium, Teflon and Viton. Teflon had the highest adhesive strength above -10°C. Stainless steel was the lowest throughout the measured range. Generally the trend was for a stronger adhesive strength at lower temperatures. This trend does not agree with my results. Their results depend slightly on the substrate materials but ranged from 30 to 70 kPa at -6.6°C, which is comparable with my results.

Laforte et al. (1983) measured the adhesive strength of accreted ice. Their measurements involved uniform accretion around an aluminum cylinder at various wind speeds and temperatures. They measured the force required to pull the cylinder away from the accreted ice. They found considerabl dependence of the growth conditions on the adhesive strength. The mode of failure of separation was mostly adhesive. Although the accreted ice in my studies is grown at a far higher wind speed than theirs, their highest adhesive strengths (which ranged from about 40 kPa at -2°C to about 180 kPa at -10°C) at the highest wind speeds are comparable to my results of 30-150 kPa.

DISCUSSION

The results of the analysis show an interesting result of the relationship between the tensile and adhesive shear strengths and the growth rate. The higher tensile strength at slower growth rates indicates that some strengthening process, such as sintering, annealing or recrystallization, is involved during ice accretion. Since no systematic difference was detected in the densities of fast- and slow-grown accreted ice, the density vs strength relationship observed by Laforte et al. (1983) is unlikely to be the cause of the difference.

The appearance of the fractured surfaces indicated that the grain sizes of slow-grown ice were smaller than the fast-grown ice. If the fracture proceeds within the grain, the Petch effect may explain the greater strength in the ice with smaller grain size. According to Shulson et al. (1982) the tensile strength σ_t, which may correspond to our tensile strength T, of randomly oriented ice at -10°C is related to the grain size d by the relationship

$$\sigma_t = \sigma_i + k \cdot d^{-1/2} \qquad (12)$$

where σ_i = 600 kPa and k = 20 kPa·m$^{1/2}$. If the grain size for faster growth is 2 mm and the grain size for

slower growth is 0.2 mm, the tensile strength is calculated to be 1050 kPa and 2010 kPa, respectively, for randomly oriented freshwater ice. The tendency seems to agree with my results but my measured values were one half of their values. This difference may be due to the difference in crystal structure. The accreted ice is mostly columnar in the temperature range of the experiments; the tensile force was applied perpendicularly to the direction of column growth, so the strength may be lower than for randomly oriented crystals.

I have little explanation to offer on the grain size vs adhesive shear strength relationship or the dependence on temperature. However, self-shedding is a dynamic process and little time was spent between the formation of ice by accretion and shedding, unlike the other studies. Droplets hitting the substrate at high speed tend to clean the surface; higher deposition rates may also result in cleaner substrate surfaces, which may give a higher adhesive shear strength. To prove or disprove such speculation and to understand the accretion problem more clearly, further experimental studies are needed.

CONCLUSIONS

Simultaneous measurements of tensile and adhesive strength of accreted ice can be made in situ simply by measuring the radius of the rotor, the location of failure surface, the ice thickness, the density of the accreted ice, and the rotor speed. The results agree with previous measurements of adhesive and tensile ice strength. This method can be used to analyze existing data to obtain little-studied values of shear adhesive and tensile strengths of accreted ice. Some new measuring methods based on this study can also be developed.

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